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Pulsar observations with the Indian X-Ray astronomy experiment

K. Mukerjee
Tata Institute Of Fundamental Research
Homi Bhabha Road, Colaba, Mumbai-400005, India.

Abstract. Observations of some X-ray pulsars were carried out by the pointed mode proportional counters of the Indian X-ray Astronomy Experiment (IXAE) on IRS-P3 satellite which has completed its three successful years of operation on 1999 March 21. The X-ray instrument details and results obtained from the observations of pulsars namely Crab pulsar, 4U 1626-67, Cep X-4 and 4U 1907+09 are discussed in this paper.

Keywords : X-Ray spectra, instruments and techniques, pulsars

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1. Introduction

X-ray pulsars are spinning neutron stars with a very high magnetic field ($B \approx 10^{12}$ gauss) which either powered by accretion of matter from its stellar companion or by the rotational energy of the neutron star. The accretted matter in the form of plasma gets channeled through the magnetic poles of the neutron star and falls at the polar caps known as the hot spots, where the gravitational energy is released in the form of X-rays and Gamma-rays. Due to rotation of the neutron star about its axis of rotation the emitted radiation pulsates with the period of the rotation of the neutron star provided there is an off-set in the axis of rotation and the magnetic axis of the neutron star. Studies of X-ray pulsars are important to understand the characteristics of the X-ray emission region, details of the accretion process and geometry of the accretion region above the magnetic poles of the neutron star. By measuring time dependent changes in the pulsation period and shape of the X-ray pulse in different luminosity states of a source, one can learn the astrophysics of the accretion process in the strong gravitational field of the magnetized neutron star in binaries. From the measured spin parameters and the pulse characteristics it is possible to infer the accretion torque, details of the pulsars magneto-sphere and the geometry of the X-ray beam and luminosity dependent changes in the beam shape. Such studies provide valuable observational tests of theories of the accretion process in X-ray binaries. Motivated with these objectives of pulsar studies, various pulsars were observed with Indian X-ray Astronomy Experiment (IXAE) during its last three years of successful operations on board the IRS-P3 satellite. These include Crab pulsar, a Low Mass X-ray Binary (LMXB) pulsar 4U 1626-67 and two High Mass X-ray Binary (HMXB) pulsars namely Cep X-4 and 4U1907+09.

This paper describes results on the pulsation characteristics of these X-ray pulsars based on the observations made with the IXAE.

2. The X-ray instrument

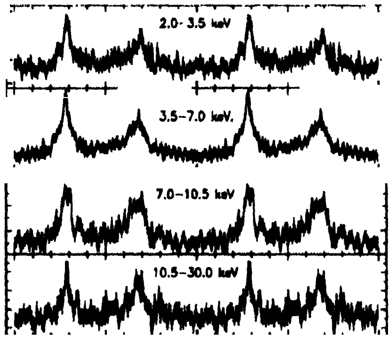
The principal instrument of IXAE is a set of three identical co-aligned multi-layer, multi-cell proportional counters named as pointed mode proportional counters (PPCs) with an effective area of about 1200 cm^2. Each PPC consists of 54 anode cells of size 11 mm $\times$ 11 mm arranged in three layers. The end cells and the third anode layers are linked together and used as a veto counter to reject the charged particle background due to cosmic rays. The alternate cells of top two layers are inter linked together and operated in mutual anti coincidence to reject non-cosmic X-ray background produced by Compton scattering of high energy photons. The PPCs are filled with P-10 gas at a pressure of 800 torr and is used as X-ray detection medium. Each PPC is having a passive collimator with a field of view of 2.3° $\times$ 2.3° and a 25 micron thick aluminized mylar film as the X-ray entrance window. Each PPC has its own command-able high voltage unit, front-end electronics, signal processing logic and pulse height analyzer. Memory allocated for individual PPC's for on-board storage of the data is 4 megabit. The PPC data are obtained in the form of X-ray counts in 2-6 keV band from top layer, 2-18 keV counts from top and middle layers, veto layer counts and counts exceeding the upper level discriminator (ULD) which is set to 30 keV. In the normal mode of operation, PPC data are sampled every 1s and 64 channel PHA information is available for every 100 s integration. The sampling time of counts and PHA is selectable with command. Other sampling modes available are 100 ms, 10 ms and 10 s for counts and 1 s, 10 s and 1000 s for PHA, independent of each other. The PPC's can be operated in the Pulsar mode as well, where every event registered in the detector is time tagged with an accuracy of 0.4 msec along with its 8 channel PHA information and layer identification. There is an on-board calibration source Cd-109 mounted in rear side of the PPC which shines on one side of the veto-cells, for constantly monitoring 22 keV line of this calibration source and is used to monitor the PPC gain. A detailed description of the IXAE is given by Agrawal et al. [1-2].

The IRS-P3 is a three-axes stabilized satellite in a circular orbit of 830 km altitude with an orbital inclination of 98° to the equatorial plane. A CCD based star tracker is used to acquire a specific target with an accuracy of better than 0.1°. Due to polar orbit of the satellite, useful data can be obtained only from 5 of the orbits which do not pass through South Atlantic Anamoly zone only in the latitude band of +50° to -30° yielding about 15 to 20 minutes of useful data in each orbit.

3. Observations

In order to detect pulsations with the PPCs, the well known Crab pulsar was observed with the IXAE. Since higher time resolution is required to detect 33 msec pulsation, the source was observed in the Pulsar mode with time resolution of 0.4 msec. From the data obtained with 10 minutes exposure of this intense source, 33 msec pulsations were clearly detected in all the three PPCs. In order to confirm the detection of pulsations in the nornal mode sampling of data, 4U 1626-67 was chosen to be the next pulsar. This is a very interesting pulsar which had undergone an abrupt change of phase, from its spin-up phase to spin-down phase sometime in 1990. The pulse period was known accurately for this pulsar from regular BATSE observations in 20-60 keV hard X-ray band. This was, therefore, the best available candidate for observations. Moreover, an additional motivation was to establish the pulse profile in the 2-18 keV soft X-ray band in order to supplement the information of this source in complete 2-60 keV X-ray band. After correcting for minor timing discrepensies observed in the data, it was possible to detect clear pulsation in the data. With these proven potential and other available logistics such as type of detector systems and available extended time for observations, it was decided to observe a few pulsars for longer durations. With these objectives in mind, two other pulsars namely, 4U 1907+09 and a transient pulsar Cep X-4 in the outburst phase were observed.

The Crab pulsar was observed in 1996 November 19 - December 3. The PPCs were operated in the Pulsar mode and normal mode during this observation. The average countrate of the PPCs during the observation was 1230 counts s^{-1} (the counts reported here are, total counts of all the three PPCs). The Pulsar mode observations were carried out to establish the timing informations of this pulsar. The second pulsar 4U 1626-67 was observed in the normal mode during 1996 August 6 and August 12-15. The results presented here are obtained from our first observation only. The pulsar 4U 1907+09 was first observed during 1996 August 4-7. An average counting rate of about 40 counts s^{-1} was detected in the PPCs during this observation. The total exposure to the source was about 16000 s. The source was observed again during 1998 May 29 - June 2 with total useful exposure of about 20000 s. The X-ray pulsar Cep X-4 underwent an outburst which lasted for 30 days during 1997 July 3 - August 4. The IXAE observed the source in its declining phase for 3



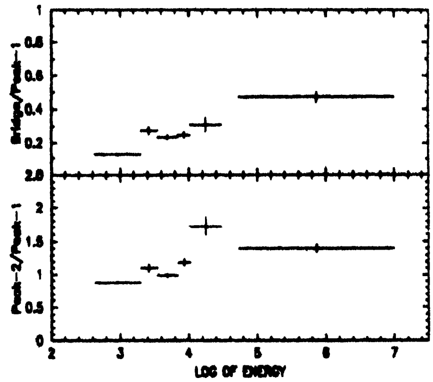


Figure 1. Pulse profiles of Crab Pulsar in 4 different X-ray energy bands obtained from IXAE observations between 2-30 keV.

Figure 2. Fluence ratios of bridge and peak-2 relative to peak-1 versus energy plot for the Crab pulsar. The fist data point in the soft X-ray region is obtained from ROSAT HRI and the last data point for gamma-rays is obtained from CGRO OSSE [3].

days during 1997 July 28-30. The total useful exposure time for this source was 12000 s. The source counting rate was 5 counts s^{-1} during the observation.

4. Results and discussion

4.1. *Crab pulsar*

The Crab pulsar is one of the best studied object in almost all the energy band of electro-magnetic spectrum. This is, therefore, an ideal candidate for study of the characteristic behavior of rotational powered pulsars and also about their emission mechanism. The Crab pulsar is located within the supernova remnant, the Crab nebula. This is a bright X-ray source of constant intensity which pulsates with the period of 33 msec in the entire band of electro-magnetic spectrum. Since the source intensity of this stellar object is used as a standard and spectral features of this source are well known, the Crab pulsar was observed as the first pulsar source in order to verify detector performance and its calibrations etc..

The pulse profiles of the Crab pulsar obtained from IXAE observations are shown in Figure 1. These profiles have sharp double pulses with a separation of 0.4 in phase between the two peaks. The first pulse is known as the primary and the second one as the secondary. Both the pulses are joined by non-zero valley region known as bridge. Detailed study of the pulse profiles obtained in 4 different energy bands between 2-30 keV shows energy dependence. The integrated flux or fluence of peak-2 and bridge with respect to peak-1 shows variation with energy as shown in Figure 2 [4]. The overall trend for the increase of the fluences of peak-2 and bridge with respect to peak-1, with energy has differing implications for each of the models for pulsar emission. None of the models namely two-gap outer gap model, one gap outer gap model or Polar cap gap model can explain completely the observed energy dependent variations in the pulse profile of the Crab pulsar. This pose a serious difficulty for the existing pulsar emission models and indicates need for further refinement of the models.

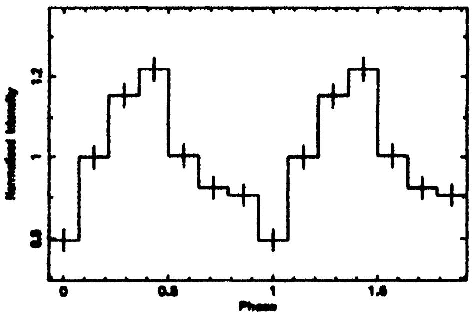
4.2. *4U 1626-67*

A Low Mass X-ray Binary pulsar 4U 1626-67, having 7.6 sec pulse period and most probable orbital period of 42 minutes, was observed to measure its pulse profile in the soft X-ray region. The results of timing analysis confirmed 7.67± 0.01 second pulsation of the neutron star of the Low Mass X-ray Binary pulsar 4U 1626-67. The pulse profile obtained by folding the data with the best-fit period gives a broad single pulse as shown in Figure 3. The pulse profile obtained by BATSE in 20-60 keV [5] is also a single pulse which appears to be comparatively more symmetric than the IXAE pulse profile obtained in the lower energy band between 2-18 keV. The measured period indicate that pulsar is still undergoing a spin-down phase after its episodic torque reversal which took place between 1990 and 1991. The period agrees well within the error with the value estimated using spin-down rate of the BATSE measurements. The abrupt change in the sign of the torque is difficult to explain on the basis of current observations of smooth variation in the pulsar period.

4.3. *4U1907+09*

The X-ray pulsar 4U 1907+09 has pulsation period of 440 s and a binary period of 8.38 days. During every binary cycle it undergoes outbursts. Its light curve shows irregular intensity variations superposed on the regular X-ray pulsations. Observations of this source were made with the IXAE in two different epochs, first during 1996 August and again in 1998 May-June to carry out pulse period related measurements and also to determine the X-ray pulse shape.

The observations of the slow pulsar 4U 1907+09 with a time gap of two years, provides us accurate measurements of pulse characteristics of this pulsar. The pulse period obtained from 1996 observations is 440.53±0.02 sec, while from the 1998 observations period is found to be 440.95±0.01. The rate of pulse period variation ($\dot{P}$) is estimated to be + 0.21 s yr^{-1}. These measurements are consistent with the measurements carried out with XTE [6]. These results indicate that the pulsar is undergoing a monotonous spin-down since



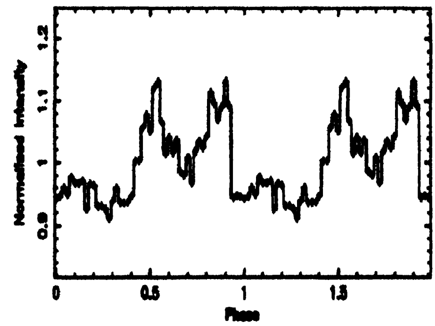


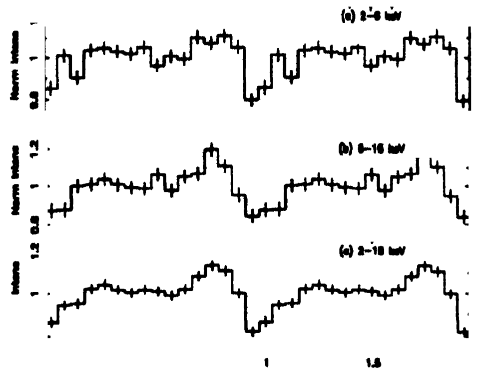
Figure 3. Average pulse profiles of 7.6 second pulsar 4U 1626-67 in 2-18 keV energy band.

Figure 4. Pulse profiles of 4U 1907+09 in 2-18 keV energy band obtained from IXAE observations in 1996.

its discovery in 1983. The average pulse profile of the source in the energy band between 2-18 keV obtained from 1996 data is shown in Figure 4. The shape of this double pulse profile does not show remarkable variation in 2-6 keV and 6-18 keV energy band. We therefore state that the pulse profile of 4U 1907+09 is energy independent in the 2-18 keV range.

4.4. *Cep X-4*

The transient X-ray source Cep X-4 was discovered in 1972 by OSO-7 satellite [8-9]. The pulse period of 66.25 s was first detected by Ginga in 1988 [10]. The energy spectrum of Cep X-4 is found to be rather hard with a power-law photon index of about 0.9 to 1.35. From the presence of a cyclotron line at 30 keV its magnetic field is inferred to be 2.6×10^{12} Gauss [11]. This source undergoes outburst in an irregular manner. The source had undergone its latest outburst in 1997 July - August. The IXAE observed this source during decline phase of its one month long outburst, in order to carry out luminosity dependent studies of this source. The spectral features of Cep X-4, observed in the optical band, was found to resemble that of a typical Be/X-ray binary system [12]. These observations along with the observed outburst activities of Cep X-4 strongly support that it is a Be/X-ray binary system. The 1997 outburst of Cep X-4 which lasted for a month, was observed by three satellites consecutively. BATSE observed the source in the initial phase of the outburst followed by RXTE [7] and finally by IXAE during its declining phase, very close to the end of the outburst. The source luminosity during IXAE observations decreased to about 2×10^{36} ergs s^{-1} whereas peak luminosity attained by the



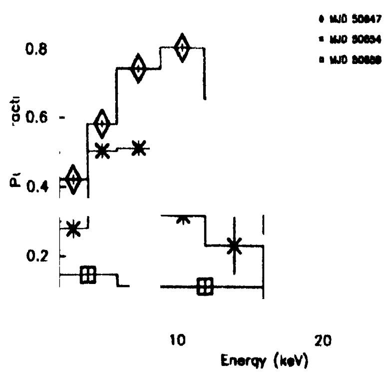


Figure 5. Pulse profiles of the Cep X-4 Pulsar at different X-ray energy bands (a) 2-6 keV (b) 6-18 keV and (c) total 2-18 keV, obtained from IXAE observations during 1997 July 28-30 (MJD 50658 to MJD 50660).

Figure 6. RMS pulse fraction measured in different energy bands between 2-30 keV during the decay of 1997 July outburst of Cep X-4. The data on MJD 50647 and MJD 50654 are adapted from [7].

source during the outburst was 2.5×10^{37} ergs s^{-1}. The pulse period measured from IXAE observations was 66.27 ± 0.03 s, which was found to be consistent during its complete outburst phase. These properties relate this outburst with the outburst activity of Class-I, which is due to the periastron passage of the neutron star in a Be-binary system [13].

The average pulse profile of Cep X-4 obtained in two energy bands between 2-18 keV, show inter-pulse dominated double-pulse profile as shown in Figure 5. This is in contrast to the double-pulse profile observed during the initial phase of observations in which the main-pulse was found to be more prominent compared to the inter-pulse. We thus notice remarkable change in the pulse profile of Cep X-4 with decay of the outburst.

The pulse fraction measured in 2-30 keV energy band during the decay of the outburst is shown in Figure 6. The decrease in RMS pulse fraction with decrease in luminosity was observed during the declining phase of the outburst. The phenomenon of decrease in X-ray pulse fraction when the source flux drops below a certain threshold, has been observed in other X-ray pulsars like GX 1+4 and GRO J1744-28 and it has been interpreted as due to centrifugal inhibition of accretion onto the neutron star and is called the "Propeller effect" [14].

For Cep X-4 the pulse period P is 66.27 s and assuming a neutron star mass of $M = 1.4\ M_\odot$, the co-rotation radius (r_{co}) can be calculated as 2.78×10^9 cm. The Cep X-4 luminosity during the IXAE observation is estimated to be

2.4×10^{36} ergs s^{-1}. Using this luminosity and magnetic field $B = 2.6\times10^{12}$ G derived by Mihara et al. [11] the magneto-spheric radius (r_m) is calculated to be 7.4×10^8 cm [15].

Thus, the co-rotation radius is about 4 times the magneto-spheric radius at this observed luminosity. The centrifugal inhibition in X-ray binary pulsar occurs when the co-rotation radius becomes equal to the magnetospheric radius [14]. It is, therefore, concluded that the decrease in the pulse fraction in Cep X-4 is not due to Propeller effect as there in no inhibition of accretion at the observed luminosity.

Pulse profile changes similar to those seen in Cep X-4 were also observed in another transient pulsar EXO 2030+375 (Parmar et al. 1989) during its outburst activity. Such changes in the pulse profile are explained due to the change in the beam pattern where either a pencil-beam or fan-beam configuration becomes more predominant with change in luminosity. Alternately, it is shown here that the observed change may be possible due to change in the accretion process at this critical luminosity when magneto-spheric changes may trigger relative change in the accretion rate on to the poles of the neutron star causing the relative change in the strength of the pulse amplitudes.

X-rays are emitted from X-ray pulsars due to the accretion of appreciable plasma onto the neutron star [17]. This plasma at the magneto-pause cools primarily by inverse Compton process. If the luminosity is greater than a critical value L_{crit} the Compton cooling time scale at the magneto-pause is shorter than the free fall time scale. The value of L_{crit} is related to other parameters [17] as

$$L_{crit} \equiv 2.0\times 10^{36}\ \mu_{30}{}^{1/4}(M/M_\odot)^{1/2}R_6{}^{-1/8}\ \text{ergs s}^{-1}$$

which corresponds to a critical mass accretion rate,

$$\dot{M}_{crit} \equiv 1.5\times10^{16}\ \mu_{30}{}^{1/4}(M/M_\odot)^{-1/2}R_6{}^{7/8}\ \text{g s}^{-1}$$

The critical luminosity estimated for Cep X-4 is $L_{crit} = 3\times 10^{36}$ ergs s^{-1} and the critical mass accretion rate is estimated to be $\dot{M}_{crit} = 1.6\times10^{16}$ g s^{-1}. Since the observed luminosity (2.4×10^{36}) during the IXAE observations and so also the rate of mass accretion (1.3×10^{16} g s^{-1}) are close to the critical values, it implies that there may be additional mode of accretion possible at this luminosity. As discussed by Elsner and Lamb [17] at the critical luminosity another entry mode of plasma may set-in through the regions of polar cusps. In this process, when there is an extensive plasma atmosphere outside the magneto-sphere, the cooling time for stagnant plasma above the polar cusp, through bremsstrahlung, is shorter than that above the equatorial magnetosphere. This will cause a pressure gradient in the plasma above the cusps accompanied by the much flatter pressure gradient in the plasma above the magnetic equator. If the pressure variation above the cusp is steeper than r^{-6} and sufficiently localized in magnetic latitude, the magnatopause in the cusps would remain stable while descending to the stellar surface, carrying the stagnant plasma with it. During the IXAE observations at such a critical luminosity, most probably, there is an onset of additional accretion onto one of the poles through the polar cusp, resulting in relatively higher accretion onto the pole. The observed change in the pulse profile of Cep X-4 during the IXAE observation is, therefore, likely to be due to relative change in the accretion onto the neutron star at this critical luminosity. Although observations of EXO 2030+375 [16] also show similar change in the profile at critical luminosity, more observations during the decay phase of such outbursts are required to confirm this scenario and lead to a deeper understanding of the accretion process at lower luminosity.

5. Conclusion

The Indian X-ray Astronomy Experiment(IXAE) have been successful in observing many interesting sources during its stellar campaign, in-spite of various limitations due to the polar orbit of the satellite and limited time due to two fold operations of remote sensing payloads. The observations of a variety of pulsars with the IXAE have revealed many interesting phenomenon occuring in these objects. Study of the energy and luminosity dependent variations in the emission profile of the pulsars, have added more knowlegde to our present understanding of the accretion process and the beaming mechanism of the pulsars. A long term study of these pulsars will provide us better understanding of some of the astrophysics related problems concerning the magnetized neutron stars.

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